Small-x Physics and Forward Jet Production at THERA

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Abstract

We discuss some aspects of forward jet production as a signature for small x physics at THERA energies.

1   Introduction

The evolution of the parton densities at small x is a very rich but complicated issue. The steep rise of the structure function F_2 at small x is explained by the presence of a huge gluon number density. The pure DGLAP [1, 2, 3, 4] evolution equations, meant to describe the evolution of the parton densities as a function of Q^2, are able to reproduce the rise of F_2 provided the input starting distributions are chosen properly.

Figure 1 shows the pattern of QCD initial-state radiation in a small-x DIS event, together with labels for the kinematics. The gluon splitting function P_{gg} is given by:

$$P_{gg}(z_i, k^2) = \bar{\alpha}_\mathrm{s} \left(\frac{1}{z_i} - 2 + z_i(1 - z_i) + \frac{1}{1 - z_i} \right) \frac{1}{k^2}, \tag{1}$$

where $\bar{\alpha}_\mathrm{s} = \alpha_\mathrm{s} C_A/\pi$ and $z_i = x_i/x_{i-1}$ (see Fig. 1) is the ratio of the energy fractions of successive branchings in the gluon chain and k^2 is virtuality of the t-channel gluon with $k^2 \sim k_t^2$. In DGLAP the k^2 dependence of all emissions in the gluon chain are simplified by the observation that at not too small x the dominant part to the cross section comes from the region of phase space where k^2 is very small. However if x or z becomes very small, the collinear (small k_t^2) approximation of
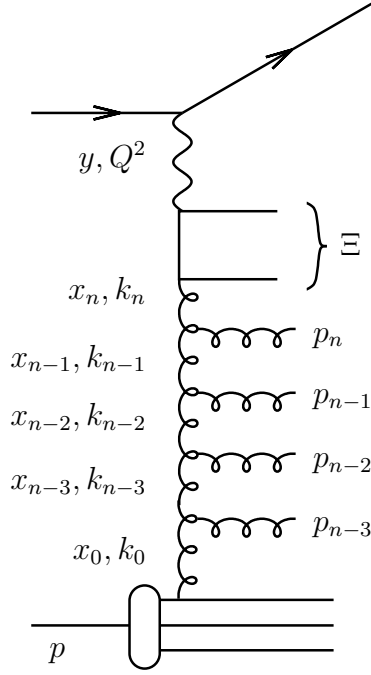
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Figure 1: *Kinematic variables for multi-gluon emission. The t-channel gluon momenta are given by k_i and the gluons emitted in the initial state cascade have momenta p_i. The upper angle for any emission is obtained from the quark box, as indicated with Ξ.*

DGLAP may be inadequate. This region is treated by the BFKL [5, 6, 7] evolution equation, which keeps the full k_t^2 integration but approximates the gluon splitting function with the asymptotic form

$$P_{gg} \sim \frac{1}{z}\frac{1}{k_t^2}.$$

From a detailed analysis of interference effects in a gluon chain, it was found [8, 9, 10, 11] that the proper evolution variable is the angle of the emitted gluon, and not the virtuality k^2 as in the DGLAP approximation, nor z as in the BFKL approximation. This angular ordering resulted in the new, and more complicated, CCFM evolution [8, 9, 10, 11], which reproduces the BFKL and DGLAP approximations in the small and large x limits respectively. The CCFM equation naturally interpolates between the two extremes. However, in CCFM the gluon

splitting function contains only the singular terms in z:

$$P_{gg} = \bar{\alpha}_{\mathrm{s}} \left(\frac{1}{z} \Delta_{ns} + \frac{1}{1-z} \right),$$

with Δ_{ns} being the non-Sudakov form factor to regulate the $1/z$ singularity. The non singular terms of the splitting function (see eq.(1)) are not obtained within the CCFM approximation.

Whereas at HERA energies ($\sqrt{s} \sim 300$ GeV) the total cross section of deep inelastic scattering can be reasonably well described with the DGLAP evolution equations, measurements of specific features of the hadronic final state indicate clear deviations from a pure DGLAP scenario.

The cross section at low x and large Q^2 for a high E_T^2 jet in the proton direction (a forward jet) has been advocated as a particularly sensitive measure of small x parton dynamics [12, 13]. If the forward jet has large energy ($x_{jet} = E_{jet}/E_{proton} \gg x$) the evolution from x_{jet} to small x can be studied. When $E_T^2 \sim Q^2$ there is no room for Q^2 evolution left and the DGLAP formalism predicts a rather small cross section in contrast to the BFKL/CCFM formalisms, which describe the evolution also in x. Measurements performed at HERA [14, 15] show that the prediction from the naive DGLAP formalism lies a factor ~ 2 below the data, whereas the data can be described by CCFM evolution equations [16].

2 Initial State QCD Cascade

The effect of new small x parton dynamics is most clearly seen if the contribution from typical DGLAP dynamics is suppressed. The forward jet production in deep inelastic scattering at small values of x is one example of such a process. However, the kinematics need to be investigated further. Typical event selection criteria at HERA are:

$$Q^2 > 10 \text{ GeV}^2$$
$$E_{t\,jet} > 5 \text{ GeV}$$
$$\eta_{jet} < 2.6$$
$$x_{jet} > 0.036$$
$$0.5 < E_T^2/Q^2 < 2$$

The range in x is typically $10^{-3} < x < 10^{-2}$. The evolution takes place from the large x_{jet} down to the small x with a typical range at HERA energies of $\Delta x = x/x_{jet} \sim 0.1 - 0.01$. In order to justify the use of an evolution equation (instead of a fixed order calculation) one would require at least 2 or more gluon emissions during the evolution. To roughly estimate the energy fractions z_i of 3
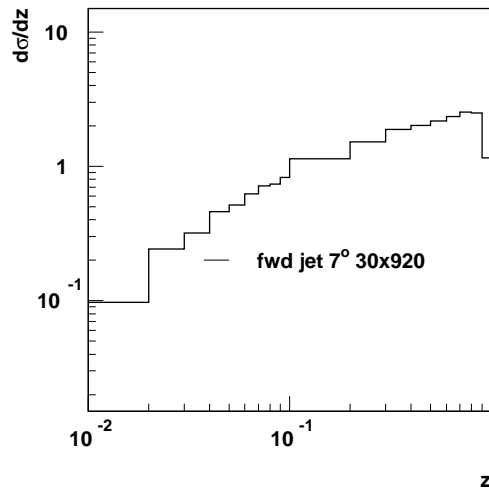
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Figure 2: *The values of the splitting variable z for events satisfying the forward jet criteria, with $\theta = 7°$ at HERA energies.*

gluon emissions between $10^{-3} < x < 10^{-1}$, one can assume that each gluon carries the same energy. Then the range of $\Delta x \sim 0.01$ results in $z \sim 0.2$, which is far from being in the very small z region, where the BFKL or CCFM approximations (treating only the $1/z$ terms in the gluon splitting function) are expected to be appropriate. In Fig. 2 we show the values of the splitting variable z in events satisfying the forward jet criteria at HERA energies obtained from the Monte Carlo generator CASCADE [16]. Since the values of the splitting variable z are indeed in the large z region (the majority has $z > 0.1$), it is questionable, whether the BFKL or CCFM evolution equations, including only the $1/z$ terms of the gluon splitting function, are already applicable. Whereas the measurement at HERA stops at $x \sim 10^{-3}$, the available phase space at THERA is enlarged by a factor of ~ 10. Therefore the gluons along the chain will presumably have smaller z values and the usage of the small x evolution equations might be more justified. In Fig. 3 we show the z values obtained from events satisfying the forward jet selection criteria at THERA energies ($\sqrt{s} = 959$ GeV) compared with the ones at HERA energies ($\sqrt{s} = 332$ GeV). The four plots correspond to different cuts on the minimum jet angle ($\theta = 1°, 3°, 5°, 7°$). One clearly can observe, that the distribution of z values becomes flat at small z at THERA energies and that the small z values are no
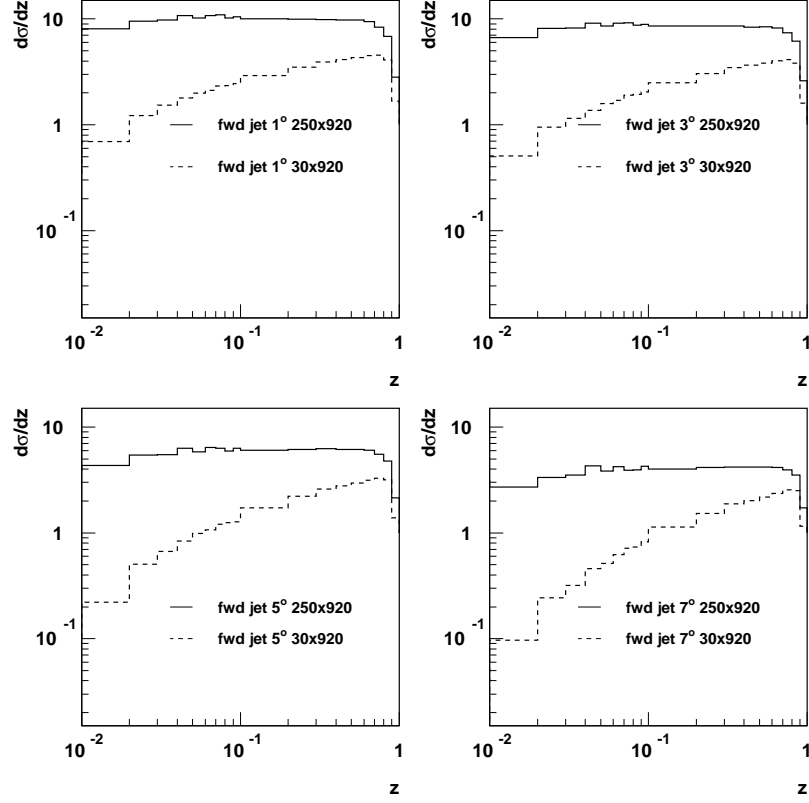
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Figure 3: *The values of the splitting variable z for events satisfying the forward jet criteria, for different cuts on the minimum jet angle: a. $\theta = 1°$, b. $\theta = 3°$, c. $\theta = 5°$, d. $\theta = 7°$. The solid line corresponds to the prediction at THERA energies, the dashed line corresponds to HERA energies.*

longer suppressed as in the HERA kinematic region. This clearly shows, that the application of small x evolution equations at THERA energies are justified and unavoidable, although the sensitivity to the treatment of large z splittings does not completely go away.

At HERA the forward jet cross section could be reasonably well described by including a resolved virtual photon contribution, because the phase space for small z emissions at HERA energies was relatively small. The situation changes at

THERA energies: the phase space for small z emissions is larger and effects from small x evolution become more visible. In Fig. 4 the cross section for forward jet production is shown as a function of x for standard DGLAP prediction (dotted), including in addition a contribution from resolved virtual photons (dashed-dotted) and the CCFM prediction (dashed). For comparison the prediction from ARIADNE[17][1] is shown, which implements a semi-classical soft radiation model in a dipole cascade, and which currently gives the best overall description of small-x HERA data. Since the the available phase space at THERA is enlarged by a factor of ~ 10, the difference between the standard DGLAP-based calculation and the CCFM calculation is increased. Moreover, at THERA the CCFM approach predicts a larger cross section than the model with resolved virtual photon contributions added, and smaller cross section than ARIADNE, while all three models give comparable results at HERA. This gives a unique opportunity, not only to distinguish between the different approaches, but also to study details of the QCD cascade in a regime, where the new small-x evolution equations should be appropriate.
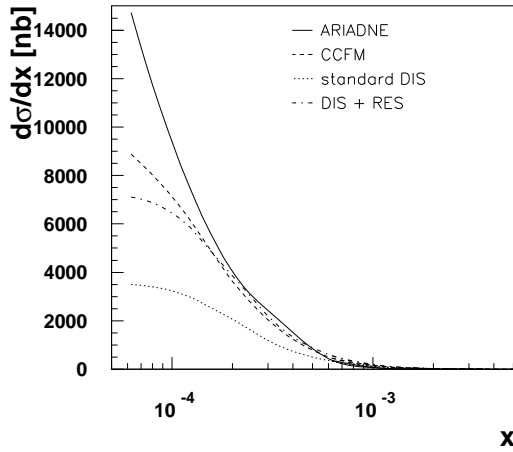

Figure 4: *Forward-jet cross section as a function of x in different models for $0.5 < p_t^2/Q^2 < 2$ and a minimum jet angle of $1°$*
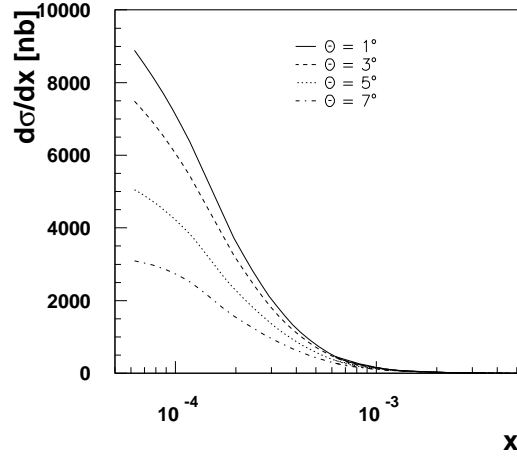
Figure 5: *Forward-jet cross section as a function of x obtained from CCFM for $0.5 < p_t^2/Q^2 < 2$, for different cuts on the minimum jet angle*

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[1]using the tuned parameters given by 'set2' in [18]

6

In Fig. 5 the forward jet cross section is shown for different minimal jet angle cuts. On the experimental side this requires complete acceptance both in the electron and proton direction down to the lowest possible angles. From the size of the cross section $d\sigma/dx$ one would like to reach at least $\theta \sim 3°$ for the forward jet measurement, but there are other reasons to ask even for $\theta \sim 1°$. On the other hand, the luminosities needed for such measurements are moderate so that this question can be settled within one year of running at THERA.

3   Conclusion

HERA has conclusively shown the need to go beyond the standard DGLAP evolution equations in order to explain the data on small-x final states. The reach in x is, however, not quite enough to really study details of the small-x evolution to be able to distinguish between different approaches, such as the CCFM evolution, resolved virtual photons and the dipole cascade model. With the increased kinematical region available at THERA, this will become possible. The steeply rising cross section as x gets smaller means that such measurements can be done even with moderate luminosity. On the other hand the demands on the forward coverage of the detector is more critical — ideally it should be possible to measure jets down to an angle of $1°$.

Once a good understanding of the small-x evolution is obtained, it should be possible to use the underlying $k_\perp$-factorization theorem in BFKL/CCFM, where observables are described in terms of process–dependent off-shell matrix element and universal un-integrated parton densities, to make firm predictions of any other small-x measurement, just as normal DGLAP parton densities and matrix elements are used today at large Q^2. THERA will be the only place where these un-integrated parton densities can be measured.

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